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The Effect of Landing Construction on Some Forest Soil Properties: A Case Study

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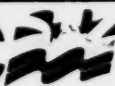
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ABSTRACT

A study of landings near Fort St. James, B.C. revealed that while summer landings were more dense than winter landings, both exceeded a bulk density of 1400 kg/m^3 , which is recognized as a level adversely affecting forest productivity. Additionally, the higher soil density was still evident at the 20-30 cm depth in both types of landings, indicating the need for soil decompaction to a depth greater than 30 cm. Soil nutrient quality on the landings also suffered from scalping during construction. The soil nitrogen and available phosphorus and potassium concentrations were substantially lower following construction. The N and P content was more severely affected by removal of surface horizons than was soil K. Although the landings were generally well-stocked with lodgepole pine, height growth suffered. Tree growth loss was greater on summer (45%) than winter (30%) landings 6 years after logging. However, 11 years after logging, growth loss was nearly equal (approximately 60%) on summer and winter landings. Landings areas cannot be expected to contribute to the future merchantable timber volume unless both the soil density and nutrient problems are solved.

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1 PROBLEM STATEMENT

In the interior forest regions of British Columbia the conventional method of harvesting timber with ground-based equipment necessitates the construction of skid roads and landings. According to an unpublished internal survey done by the Ministry of Forests in 1983, landing areas occupy an average of 4-5% of cutover land, and skid roads approximately 16%. In steeper terrain the overall extent of the landings will decline slightly, but skid road areas can increase to at least 30% (Hatchell *et al.* 1970; Froehlich 1973; Smith and Wass 1979; McLeod and Hoffman 1984¹).

The construction of skid roads and landings alters soil physical and chemical properties. The degree and extent of changes in soil properties due to soil compaction or the exposure of more dense subsoil material are often dependent on site conditions during construction, its period of operation, and soil type (van der Weert 1974). Furthermore, the resulting effect on site productivity is a complex interaction between soil type, the impact on chemical and physical properties, and tree species (Greacan and Sands 1980).

Most of the literature on the consequences of disturbance caused by ground-based logging is from the U.S., New Zealand, and Australia, and concentrates on skid roads and their impact on such soil physical properties as bulk density and associated soil characteristics. Only one paper by Hatchell *et al.* (1970) mentions the log-deck or landing. The effect on soil nutrient levels is briefly discussed in papers by Youngberg (1959), Smith and Wass (1979), and Greacan and Sands (1980), but it is not quantified. Such studies, however, provide the data base and rationale for the Ministry of Forests and Lands landing and skid road rehabilitation guidelines.

At present, all the interior forest regions have recommended rehabilitation guidelines applicable to landings and main skid roads. These generally call for soil decompaction to a depth of 30 cm and replacement of removed topsoil. However, there has been no documentation in British Columbia of the depth of compaction on these areas, nor evidence that 30 cm is an adequate ripping depth. Furthermore, both past and present landing construction practices make replacement of topsoil nearly impossible. Soil development in the interior regions of British Columbia is restricted in depth, and the removal and stockpiling of a thin layer of topsoil with current equipment in the presence of stumps and other vegetation is often impractical. Similar to most mined land reclamation, subsoil is normally the base material from which site productivity may be recovered.

A case study was conducted in British Columbia to determine the nature of the residual soil material after landing construction. Such data are applicable to main skid roads. Soil physical and chemical data were collected to serve as a basis for the development of effective rehabilitation management practices. As well, information on conifer regeneration was gathered to assess the impact of landing construction on forest productivity.

¹ McLeod, A. and E. Hoffman. 1984. A pilot study of soil disturbance on selected cutovers in the Prince George Forest Region. B.C. Min. For., Prince George, B.C. Unpublished report.

2 CONSEQUENCES OF LANDING CONSTRUCTION ON FOREST SOIL

2.1 Increased Soil Density

The influence of site degradation on many soil physical properties is closely associated with increases in soil density. For the most part, the increase is a result of compaction caused by construction and harvesting equipment. However, the removal of surface horizons during construction (scalping) or accelerated erosion can also expose denser subsoil materials, similar in traits to compacted soils. The increase in soil density is usually at the expense of soil macropores which, in turn, affect soil air, water, and temperature regimes (Ruarck *et al.* 1982). The impact of the increase in soil density will be discussed in terms of soil compaction, although this may not necessarily be the cause.

Soil bulk density is the most commonly used measure or index of soil compaction. However, variations in other soil physical conditions, for example soil texture or soil moisture, make it difficult for meaningful comparisons of bulk density differences to be made among soil types. Increases in soil bulk density from compaction are greatest at the soil surface and decline rapidly with depth. The reported increases in bulk density in the surface soil layer (0-10 cm) have ranged from 15% (Steinbrenner and Gessel 1955) to 20% (Dickerson 1976) on skid roads, and 15 to 50% on landings (Perry 1964). The increases on skid roads taper off quickly at the 10-20 cm depth (Haines *et al.* 1975; Froehlich 1973; Wert and Thomas 1981; Gent *et al.* 1983; McLeod²).

In addition to showing increases in bulk density, compaction studies have measured decreases in soil macropore structure that are up to 68% (Dickerson 1976). Similarly, decreases in air permeability, water infiltration, and hydraulic conductivity have been well documented.

The persistence of these negative impacts on the soil is varied. Dickerson (1976) estimated the recovery period of soil physical properties in the skid track to be 12 years and between track soil to be only 8 years. Thorud and Frissel (1976) found that soil bulk density recovered within 8 3/4 years in the 0- to 7.6-cm layer, but no recovery in the 13.2- to 19.6-cm layer. Wert and Thomas (1981) observed a recovery of bulk density in the 0- to 15-cm layer after 32 years, but no change at 20-30 cm. Jakobsen (1983) found the effects on bulk density and hydraulic conductivity still evident after 32 years, and Perry (1964) estimated at least 40 years were required for the recovery of log decks. The magnitude and longevity of the negative impacts of soil compaction have a great influence on tree growth and site productivity.

2.2 Removal of Surface Soil Horizons

The removal of surface soil horizons, whether it be the organic horizon (forest floor) only or down through the B or C horizons, drastically affects the functions of soil. The forest floor protects and maintains surface soil structure, which in turn controls water and air movement in the soil. It also plays an important part in the modification of soil temperature. In conjunction with the A and B horizons, it provides both habitat and food source for soil macro- and micro-organisms (Ballard 1980b). As well, the importance of the surface horizons on site nutrient capital cannot be overstated.

In a review of soil aeration, Cannel (1977) addresses the influence of increased soil density and reduced porosity on soil chemical and biological activity. Reduced soil aeration due to compaction decreases root respiration and microbial activity. Poor aeration, as well as lower soil penetrability, have also resulted in decreases of mycorrhizal growth and penetration (Skinner and Bowen 1974; Mitchell *et al.* 1982).

²McLeod, A. 1983. A pilot study of soil compaction on skid trails and landings in the Prince George Forest Region. B.C. Min. For., Prince George, B.C. Unpublished report.

A key factor affecting tree nutrition is the removal of nutrient-rich organic and surface horizons that often accompanies logging activity and accelerated soil erosion. The importance of surface soil horizons on site nutrient capital is demonstrated in studies by Cole *et al.* (1967) and Turner and Singer (1976), among others. The importance to tree nutrition of even thin organic horizons is also shown by Cole *et al.* (1974) and Kimmins and Hawkes (1978). Herring and McMinn (1980), studying site preparation, attributed regeneration nutrient problems to the removal of organic matter during scarification.

2.3 Tree Growth and Forest Productivity

Soil degradation due to forest harvesting activities results in the reduction of the capacity of a site to produce commercial timber. The establishment, development, and growth rate of commercial species are adversely affected by increases in soil density and the removal of surface soil horizons. The magnitude of this impact depends on the extent of the affected area and degree of disturbance, soil type, and tree species (Cannell 1977; Halverson and Zisa 1982).

Increases in soil density affect soil strength and aeration, which influence seedling establishment, development, and growth rate. Although the effects of soil strength (normally directly related to bulk density) and soil aeration are difficult to separate, several studies define critical values for bulk density above which root growth and development are affected. Bulk densities above 1400 kg/m^3 restrict loblolly pine root growth, branching, and penetration (Mitchell *et al.* 1982; Gent *et al.* 1983). Hildebrand (1983) found that densities of 1250 kg/m^3 in loamy soils hindered root penetration and development of beech seedlings, and that density of 1350 kg/m^3 halted root growth. Minko (1975) claims 1500 kg/m^3 to be a critical density for radiata pine growth in a silty-clay nursery soil, with seedling height and root development improving as the soil density approached 1200 kg/m^3 . Heilman (1981) demonstrated a decline in Douglas-fir seedling root penetration in loam and sandy loam soils, as the bulk density increased from 1330 to 1770 kg/m^3 , with a maximum of 1730 - 1830 kg/m^3 . Although seedlings can establish and grow in high density soils, their rate of growth is greatly retarded. A reduction in tree growth rate observed on the scour portions of landslide areas may result from the exposure of denser subsoil materials and the loss of surface soil horizons (Miles *et al.* 1984; Smith *et al.* 1983).

Regeneration delays and reduced stocking levels have been reported in conjunction with increases in soil density due to compaction (Steinbrenner and Gessel, 1955; Hatchell *et al.* 1970; Smith and Wass 1979; Wert and Thomas 1981). The reported estimates of volume reduction on skid roads range from 45% after 26 years (Perry 1964) to 74 and 80% after 32 years (Wert and Thomas 1981; Jakobsen 1983, respectively). Volume reduction estimates pro-rated over the entire cutover area are 11.8% (Wert and Thomas 1981) and 12-15% (Smith and Wass 1979). Not only are lower growth rates, regeneration delays, and reduced stocking levels incurred on areas subject to accelerated erosion or mass wasting, but the upper portions of slide areas may be considered non-stockable because of impenetrable or unstable substrata (Smith *et al.* 1983; Miles *et al.* 1984). Such areas may be lost from commercial timber production for an extended period of time.

3 OBJECTIVE

The objective of this project was to gather basic information regarding the impact of landing construction on soil properties and regeneration performance. These data are important for the development of effective landing rehabilitation guidelines and for the proper classification of such areas in the forest inventory system. The following three groups of information were collected for comparative analysis for landings and adjacent areas:

1. spatial nature of soil density
2. effect on soil nutrient content and concentration
3. effect on regeneration performance.

4 LIMITATIONS

The effect on site productivity that results from increased soil density is a complex interaction between soil type, the impact on soil chemical and physical properties, and tree species. To accomplish the objective of this study, soil type and tree species were selected so as to be constant throughout the project. Only one soil type was studied because of cost restraint. Lodgepole pine (*Pinus contorta*) was the only commercial species that regenerated within the study area in adequate numbers to allow a performance comparison on compacted soils. This removed confounding factors from the study, but does limit the applicability of these results to other areas. However, the results and general conclusions from this project should assist in the development of effective landing rehabilitation guidelines throughout the interior regions, and promote a greater awareness of the effect of ground-based logging on future site productivity.

5 STUDY LOCATIONS AND METHODOLOGY

To accomplish the objectives within the limited budget, a homogeneous plateau in the Prince George Forest Region was chosen as the study area. Six cutblocks of similar pre-logging stand composition and timber yield were used as experimental units. These stands, within the same soil type and ecosystem unit classification, were stratified by season of logging (summer or winter). Each cutblock had at least four landing areas of full-bench construction. An additional requirement of the experimental units was that the age of the stands within the season of logging strata be parallel. In this case, stand ages were chosen as 1, 6, and 11 years post-logging. This allowed for some general stand comparison regarding regeneration performance.

5.1 Site Description

The study area was located approximately 40 km northwest of Prince George, near Mossvale. The cutblocks chosen for study are bound by Bugle Lake and Mossvale Lake to the north, and Lamb Lake and Twin Bay Lake to the south. The area coordinates are 123°30' ($\pm 2'$)W and 54°225' ($\pm 5'$)N. Located on the Nechako Plain of the Interior Plateau (Holland 1964), the parent material is a gravelly glaciofluvial deposit with a sandy loam-loamy sand texture. Farstad and Laird (1954) classified this area as part of the Chilako Stony Sandy Loam complex. A more recent soil classification (Cotic *et al.* 1976) identifies the area as a Degraded Dystric Brunisol (probably Eena or Deserter Series). The area lies within the Sub-Boreal Spruce biogeoclimatic zone (Krajina 1965) and was recently classified by DeLong and McLeod (1985) as a SBSe2-05 or submesic pine-feathermoss ecosystem unit. Unlogged stands are a complex of *Pinus contorta* - *Picea glauca* x *engelmannii* - *Vaccinium membranaceum* - *Cornus canadensis* - *Pleurozium schreberi*. The moisture regime is submesic-mesic and the nutrient regime submesotrophic-mesotrophic. Timber volumes in this area average 350 m³/ha. The landings averaged 0.4 ha in size, which is typical for this region.

5.2 Spatial Nature of Soil Density

To indicate soil degradation, a difference in soil bulk density between paired observations points within the six cutblocks was chosen. One pair of observations was taken at each landing. The point of measurement within the landing was randomly selected from the portion of the landing midway between the landing centre and the outer edge. The off-landing measurement was taken 15-20 m from the outer edge of the landing, on the same line from the plot centre as the inside point. Care was taken to avoid skid roads for the outside measurement. Bulk density determination was made with a single probe nuclear densiometer (MC-1, Campbell Pacific Nuclear Corporation).

To assess the spatial nature of soil compaction on landing areas, density measurements were taken at three probe depths (10, 20, and 30 cm), which resulted in an integrated average density over that depth (0-10, 0-20, and 0-30 cm). To calculate the density over the probe depth, three replicate readings (or radiation counts) were taken at 120 intervals around the probe. A soil moisture reading was taken with each density measure to allow for soil density correction into a dry weight basis. The soil density and moisture data were then used in standard calibration equations, developed for this densiometer and probe depth, to calculate soil bulk density. The effect of soil depth on soil compaction was studied by calculating algebraically the density of three layers (0-10 cm, 10-20 cm, and 20-30 cm).

Analysis of variance (ANOVA) was performed on the bulk density data for the 0- to 30-cm profile as well as the individual layers. A split-plot model is used for the ANOVA, with season of logging representing the main effect and landing versus off-landing representing the split-plot factor.

5.3 Effect of Landing Construction on Soil Nutrient Content and Concentration

The soil nutrient status (content and concentration) of nitrogen (N), phosphorus (P), and potassium (K) was determined for the landing and off-landing area in each cutblock. The paired observations (landing and off-landing) were taken at the four landings selected for the bulk density section. Two soil subsamples were taken at each landing and off-landing area. The selection of sampling points used a procedure similar to that described in Section 5.2. These sampling points later served as plot centres for the regeneration assessment.

Soil samples within the landing were taken to a depth of 30 cm using a 5-cm diameter corer. Samples were stored in plastic bags for transportation. Because procedures used for nutrient analysis of organic matter differ from those for mineral soil, the profile sample for the off-landing area was separated into two components, organic and mineral. The organic horizon sample was taken with the use of a cutting ring 7.6 cm in diameter and 4.0 cm deep. This sample was always taken to a constant depth and a weight correction for mineral content was made later (see below). Next, a soil sample was taken of the remaining profile, to a depth of 26 cm. The subsamples were bagged separately and labelled so that reconstruction of the nutrient profile could be made after analysis. Data comparison was based on the top 30 cm of rooting medium, rather than the top 30 cm of mineral soil.

Sample preparation and analysis were conducted at Pacific Soil Analysis Inc., Vancouver. Soil samples were air-dried for at least 24 hours, separated into coarse (≥ 2 mm) and fine (< 2 mm) fractions, and weighed. The fine fraction was used in the chemical analyses. The organic horizon samples were oven-dried at 80°C for 24 hours, weighed, and ground in a Wiley Mill fitted with a 1-mm sieve. This material was then analyzed for N, P, and K content.

All laboratory analysis procedures were based on the *Methods Manual — Pedology Laboratory*, Department of Soil Science, UBC (Lavkulich 1977) except where noted. The following analyses were performed:

- soil pH: determined in 0.01 M CaCl₂ using a combination electrode pH meter;
- total soil N: using a semi-micro Kjeldhal digest with colorimetric determination, using a Technicon autoanalyzer
- available soil P: using the Bray P-1 method;
- available soil K: using a Morgan's extraction (1.0 N NaOAc) in conjunction with atomic absorption determination;
- organic horizon N,P,K: using a Caro's acid digest with N and P colorimetrically determined on a Technicon autoanalyzer and K measured by atomic absorption.

An additional step was taken to correct the organic horizon weight for mineral particles which may have been incorporated during sampling. This procedure was similar to that used by Kimmins and Hawkes (1978). A 1.000-g subsample from each milled organic horizon sample was dry-ashed, the residual material weighed, and the percentage calculated. This residual percentage, less 10%, was assumed to be mineral particles and the original sample mass was corrected to an organic matter mass basis. The choice of 10% was based on experience at the Pacific Soil Analysis Inc. laboratory with organic samples (W. Herman, pers. comm., 1984).

Analysis of variance using a split-plot model was performed on both the nutrient content and soil concentration data. Comparisons are based on the top 30 cm of rooting medium, which in the case of the off-landing areas included 4 cm of forest floor.

5.4 Effect of Landing Construction on Regeneration Performance

The paired observation points used in Section 5.3 served as centres for paired observation plots to assess regeneration performances on the 6- and 11-year old cutblocks. Stocking assessment was based on standard Ministry of Forests and Lands procedures. The plot size was 50 m² and the target stocking was 1200 well-spaced trees per hectare (or 6 well-spaced trees per plot at 2.87 m inter-tree spacing). All well-spaced trees had to be of acceptable quality and capable of becoming a crop tree. The height of the five largest, well-spaced lodgepole pines in each plot was measured to the nearest 0.5 cm, and a composite sample of current year's foliage was taken from the upper one-quarter of each measured tree. Foliage N, P, and K concentrations were measured by a Caro's acid digest; N and P were determined colorimetrically on a Technicon autoanalyzer; and K was measured by atomic absorption (Ballard 1980a).

Because of the low number of natural regenerated spruce (*Picea glauca*) on the landings, only lodgepole pines were selected for height growth and foliar analysis.

The regeneration performance data were analyzed on a stand basis. A comparison of sample means was based on a t-test for paired observations, with four pairs per cutblock.

6 RESULTS AND DISCUSSION

6.1 Spatial Nature of Soil Density

The soil bulk density data for the 0- to 30-cm profile depth, as well as the calculated layers for the two seasons of logging, are presented in Table 1. The ANOVA's (Appendix 1) indicate a significant increase in soil density due to landing construction at all depths. The presence of higher soil density levels even in the 20- to 30-cm layer for both seasons of logging agrees with studies by Perry (1964), Froehlich (1973), and Wert and Thomas (1981). This would suggest that the depth of decompaction or ripping during landing rehabilitation activities should exceed 30 cm and may need to be more in the range of 40-50 cm. Ripping to a 40- to 50-cm depth in compacted soil for improved seedling survival has been recommended (Potter and Lamb 1975; Anonymous 1977).

The ANOVA also indicates a significant treatment x season interaction for all but the 0- to 10-cm layer (Appendix 2). An interpretation of the interaction obtained by using the percent increase in soil density (Table 2) reveals a greater increase in soil density due to summer logging, except for the 0- to 10-cm layer. The degree of increased soil density declines with depth for both seasons of logging, but more rapidly for the winter logging. During winter logging, snow may reduce compaction from heavy equipment and frozen soil conditions may increase the resistance to compaction. Additionally, such a combination of conditions can alleviate the need for deep scalping of the soil to provide a firm operating surface for logging equipment. This latter factor appears to contribute to the lower increase in soil density on the winter-logged areas, as the density of the 0- to 10-cm layer within the landing is equivalent to the 20- to 30-cm layer outside the landing (Table 1). The lower increase in soil density due to winter logging agrees with results from winter logging in Minnesota (Mace *et al.* 1971).

TABLE 1. Comparison of soil bulk density (kg/m^3) by depth for summer and winter logging

Area	Depth (cm)			
	0-10	10-20	20-30	0-30
<u>Summer logging</u>				
Off-landing	860 ± 30^a	1170 ± 30	1290 ± 30	1100 ± 30
Landing	1630 ± 40 **	1930 ± 20 **	1820 ± 20 **	1730 ± 30 **
<u>Winter logging</u>				
Off-landing	830 ± 170	1150 ± 120	1300 ± 110	1090 ± 120
Landing	1380 ± 150 **	1550 ± 100 **	1620 ± 110 **	1510 ± 100 **

^a Values are means $\pm$ SE of three replications with four subsamples.

^b ** denotes significant difference at the 95% level of probability using ANOVA.

TABLE 2. Increase in soil bulk density on the landing areas as a percent of the off-landing area

Season of logging	Depth (cm)			
	0-10	10-20	20-30	0-30
Summer	89 ± 10^a	53 ± 6	43 ± 5	62 ± 4
Winter	66 ± 23	36 ± 5 _{a,b}	26 ± 2 **	39 ± 8 *

^a values are means $\pm$ SE of three replications with four subsamples.

^b * and ** denote significant difference at the 90% and 95% levels of probability, respectively, using ANOVA.

Although the summer landings were subject to a greater increase in soil density than winter landings, both have overall densities (0-30 cm) greater than 1500 kg/m³. Soil bulk densities greater than 1300-1400 kg/m³ have been shown to be critical levels for root growth and development of certain tree species. Therefore, while summer landings were subject to a greater increase in soil density than winter landings, in both cases increased density levels can adversely affect seedling root growth and eventual site productivity.

6.2 Effect of Landing Construction on Soil Nutrient Content and Concentration

Standard landing construction practices in the study area involve the displacement of the forest floor and surface mineral soil (to at least 20cm) to create a firm operating surface for equipment. Since the stockpiling and recovery of this nutrient-rich soil material is impractical in most locations (at least for present construction practices and typical soil conditions), the residual soil material has to be the basis for any future forest productivity. In this section, the effect of soil displacement (scalping) during landing construction, both on soil nutrient content (to a depth of 30 cm) and nutrient concentration, is reported. It must be remembered that the landing areas contain more soil mass per unit volume (62 and 39% for summer and winter landings, respectively) -- although of poorer quality -- than do off-landing areas. Because of high soil density, the availability of this nutrient pool for tree use may be limited. The data on the quality of residual soil material on an equal mass basis (percent concentration) may be of greater importance to landing rehabilitation, given that most rehabilitation measures include decompaction.

6.2.1 Nitrogen

Soil N content and concentration for landing and off-landing areas are presented in Tables 3 and 4. Statistical analysis for the effect of landing construction on N content indicates there is no significant difference between landing and off-landing areas (Appendix 3). There is, however, a significant decrease in N concentration due to landing construction (Appendix 4). Landing construction resulted in the removal of the forest floor, which accounted for 15% of the winter- and 20% of the summer-logged areas' N pool, and the exposure of mineral soil with lower N content. The impact of scalping was offset by the increase in soil density of the residual soil on the landing. If the off-landing area has sufficient N content for commercial forest production, it could be assumed that the same holds true for the landing. However, the increase in resistance to root penetration and decrease in soil aeration because of higher soil density in the landing would seem to limit the accessibility of the 0- to 30-cm layer's N content, which may impede tree growth.

Soil decompaction measures during landing rehabilitation, to alleviate the problems associated with high soil density, would induce a corresponding decrease in soil N content in the "new" (less compact) 0- to 30-cm layer. Reduced tree growth could be expected on decompacted landings because of lower N content in this root-accessible soil layer. This appears to be the case in the studies by Hatchell (1981) and Berg (1975) where fertilizer additions to ripped skid roads resulted in a further increase in seedling height growth. Landing rehabilitation measures may need to deal with both soil physical properties and soil fertility if full recovery of site productivity is desired.

TABLE 3. Soil N content (kg/ha) by season of logging

Season	Off-landing area				Landing area 0 - 30 cm
	0 - 4 cm ^a	4 - 30 cm ^b	Total		
Summer	250 ± 60 ^c	1401 ± 80	1660 ± 60	ns ^d	1450 ± 60
Winter	340 ± 70	1400 ± 200	1740 ± 270	ns	1710 ± 330

^a Total N from Caro's acid digest, weight corrected.

^b Total soil N.

^c Values are mean ± SE for three replications of four subsamples.

^d ns denotes no significant difference between off-landing and landing totals.

TABLE 4. Soil N concentration (%) by season of logging

Season	Off-landing area		Landing area
Summer	0.060 ± .001 ^a	** ^b	0.037 ± .003
Winter	0.078 ± .007	**	0.053 ± .012

^a values are means ± SE for three replications with four subsamples.

^b** denotes a significant difference at 95% level of probability between off-landing average and landing estimate.

6.2.2 Phosphorus

Soil P content and concentration data are presented in Tables 5 and 6, respectively. Statistical analysis confirms a highly significant decrease in the soil P content of landing areas because of scalping during construction and operation (Appendix 5). Unlike the soil N content, the increase in soil density was not enough to offset the removal of the forest floor (0-4 cm) and the surface mineral soil. The soil P pool is highly dependent on the P associated with the soil organic matter (39% for the summer- and 59% for the winter-logged stands). Additionally, the scalping of the surface mineral soil has resulted in exposure of soil that is lower in available P concentration (Appendix 6). Although the summer-logged stands have a higher P content than the winter-logged stands, both are extremely sensitive to the removal of surface soil horizons. The decline in soil P content on the landing areas (80% for summer- and 74% for winter-logged stands) may be even greater, as the accessibility of the dense soil to root exploitation is limited. As with the soil N concentration on landings, the low available soil P level of the residual soil material may point to the need to address soil fertility problems during landing rehabilitation.

6.2.3 Potassium

The effects of landing construction on the soil K pool are similar to those encountered with soil N. The soil K content (Table 7) was not significantly affected by soil scalping (Appendix 7). Although the forest floor (0-4 cm) accounted for 46% of the K content on summer- and 39% on winter-logged stands, the increase in bulk density of the residual soil material on the landing offset this loss. When compared to the off-landing mineral soils, the soil K concentration of the residual soil (Table 8) was not adversely affected by scalping, as was the case with soil N (Appendix 8). The soil K concentration is highly dependent on mineral weathering but not, as are soil N and P, with humification and mineralization (Thompson 1978). While an overall decline in soil K content did not occur, the loss of the readily available and easily accessible K may be of considerable importance to the future tree growth.

TABLE 5. Soil P content (kg/ha) by season of logging

Season	Off-landing area			Landing area 0-30cm
	0-4cm ^a	4-30cm ^b	Total	
Summer ** e	61 ± 6 ^c	101 ± 29	162 ± 30	*** ^d 35 ± 6
Winter	47 ± 5	34 ± 5	81 ± 9	*** 21 ± 6

^aTotal P from Caro's acid digest.^bAvailable soil P.^cValues are mean ± SE for three replications of four subsamples.^d***denotes a significant difference at the 99% level of probability between off-landing and landing totals.^e**denotes a significant difference at 95% level of probability between summer-logged and winter-logged stands.

TABLE 6. Soil P concentration (ppm) by season of logging

Season	Off-landing area	Landing area
Summer	45 ± 26 ^a	*** ^b 9 ± 1
Winter	16 ± 4	*** 6 ± 2

^aValues are means ± SE for three replications of four subsamples.^b*** denotes a significant difference at 99% level of probability between off-landing average and landing estimate.

TABLE 7. Soil K content (kg/ha) by season of logging

Season	Off-landing area			Landing area 0-30cm
	0-4cm ^a	4-30 ^b	Total	
Summer	84 ± 12 ^c	99 ± 13	182 ± 11	ns ^d 188 ± 27
Winter	78 ± 4	128 ± 18	206 ± 14	ns 162 ± 41

^aTotal K from Caro's acid digest.^bAvailable soil K.^cValues are means ± SE for three replications of four subsamples.^dns denotes no significant difference between off-landing and landing totals.

TABLE 8. Soil K concentration (ppm) by season of logging

Season	Off-landing area	Landing area
Summer	49 ± 4 ^a	ns ^b 53 ± 11
Winter	61 ± 11	ns 47 ± 15

^aValues are means ± SE of three replications with four subsamples.^bns denotes no significant difference at the 95% level of probability.

6.2.4 Summary of effects on nutrients

Overall, the soil P pool is the most sensitive to scalping during landing construction. The removal of the forest floor, combined with the exposure of substantially poorer quality soil material (as indicated by soil concentration) results in a much reduced P pool available for plant growth. The soil N and K pools behave similarly, with a large loss of nutrients from the removal of the forest floor being offset by the increase in soil density of the residual mineral soil. However, the accessibility of these nutrients for plant use in the denser residual soil is suspect. If rehabilitation measures do not address soil fertility problems, forest productivity on such areas may suffer.

6.3 Effect of Landing Construction on Regeneration Performance

In the two previous sections of this study, it has been shown that landings have much higher bulk density and poorer soil quality than cutover lands. However, it is difficult to use these factors alone to predict confidently a decline in forest yield. Tree growth involves complex interactions; if air, water, and nutrient supplies meet the growth requirements, growth will not necessarily be impaired by a restricted root system or low soil nutrient concentration.

To ascertain the effect of landing construction on site productivity, conifer regeneration performance factors were measured in the four older cutblocks. For each stand, differences between landing and off-landing areas in seedling stocking, seedling height growth, and foliar nutrient status were determined. Although assessment of the long-term impact of landing construction on future site yield is beyond the scope of this study, general inferences based on the data are possible.

6.3.1 Regeneration stocking

The regeneration survey was based on well-spaced trees, rather than total stocking, and the target figure for satisfactory stocking was 1200 seedlings (or trees) per hectare. The results of the stocking survey are presented in Table 9. Statistical analysis indicates no construction-related decrease in the stocking of landings, and shows generally acceptable stocking levels.

6.3.2 Foliar nutrient concentration

The foliar nutrient concentration for N, P, and K are presented in Table 10. Statistical analysis of each stand reveals a significant difference in foliar N for the 11-year-old summer landings as compared to the off-landing areas. The significant decrease in foliar N concentration in the 11-year-old summer landings is biologically important. The foliar N level on the landing area is below the acceptable threshold for lodgepole pine (1.2%), suggesting deficiency in soil N availability (Ballard 1980a). Although the N content on the landings is comparable to the off-landing areas, the landings on this cutblock are denser than the landings on the 11-year-old winter-logged cutblock (1750 versus 1480 kg/m³, respectively). It appears that the seedlings in the older, denser summer landings may be demonstrating the effects of soil nutrient depletion over time as the result of a restricted root zone. This would be expected, based on the effect of high soil density on root development.

TABLE 9. Regeneration stocking survey (stems/ha)

Year post logging Season	Off-landing area	Landing area
6 Summer	1225 ± 75 ^a	900 ± 147ns ^b
Winter	1300 ± 58	1075 ± 150ns
11 Summer	1325 ± 111	1225 ± 103ns
Winter	1325 ± 48	850 ± 168ns

^aValues are means ± SE of four estimates with two subsamples.

^bns denotes no significant difference at the 90% level of probability between off-landing and landing averages using t-test for paired observations.

TABLE 10. Foliar N, P, and K concentration (%)

Year post-logging Season	Off-landing area	Landing area
N		
6 Summer	1.57 ± .02 ^a	1.61 ± .02
Winter	1.52 ± .03	1.49 ± .02
11 Summer	1.49 ± .04	1.26 ± .03 ^{a,b}
Winter	1.46 ± .05	1.48 ± .02
P		
6 Summer	0.170 ± .003	0.176 ± .003
Winter	0.158 ± .001	0.162 ± .004
11 Summer	0.159 ± .008	0.142 ± .004
Winter	0.148 ± .004	0.155 ± .003
K		
6 Summer	0.643 ± .014	0.690 ± .010
Winter	0.637 ± .015	0.603 ± .027
11 Summer	0.559 ± .011	0.556 ± .012
Winter	0.577 ± .012	0.581 ± .019

^aValues are means ± SE of four estimates with two subsamples.

^b** denotes a significant difference at the 95% level of probability between off-landing and landing N concentration using t-test for paired observations.

6.3.3 Seedling height

Statistical analysis of the seedling height data presented in Table 11 indicated a significant effect of landing construction on the 6-year-old and 11-year-old cutblocks, respectively. Seedling height on the 6-year-old summer landings averaged only 54% of that on the off-landing area, while the winter landings averaged 72%. The difference was more pronounced on the 11-year-old cutblocks, 42 and 38% for summer- and winter-logged areas, respectively. This trend of greater height difference between off-landing and landing areas could persist for some time. It appears that the higher soil density of the landing areas, combined with the poorer nutrient soil quality, is adversely affecting height growth. It is very doubtful that these landing areas will produce merchantable timber in the normal rotation age for this forest type, although at the time of a regeneration survey such areas would be considered fully stocked. The inclusion of such landing areas in an allowable cut calculation may therefore result in overcutting.

TABLE 11. Seedling height (cm) for all stands

Year post-logging Season	Off-landing area	Landing area
6 Summer	74 ± 8 ^a	40 ± 11 ^{a,b}
Winter	88 ± 5	63 ± 9 ^{**}
11 Summer	283 ± 24	120 ± 17 ^{**}
Winter	266 ± 15	100 ± 25 ^{**}

^a values are means ± SE of four estimates with two subsamples.

^b** denotes a significant difference at the 95% level of probability, respectively, between off-landing heights using t-test for paired observations.

7 SUMMARY AND CONCLUSIONS

Although construction of summer landings resulted in greater soil density at the deeper depths than did winter landings, in both cases increased soil density was sufficient to affect tree growth adversely. When compared to that in off-landing areas, the increase in soil density of landings was greatest at the soil surface, declined rapidly with depth, and was still influential at the 20- to 30-cm depth. To fully alleviate this problem in future, soil decompaction measures during landing rehabilitation may have to go to 40 or 50 cm in depth.

The residual soil material on landing areas was of relatively poor quality compared to off-landing areas, as rated by nutrient concentration. The removal of surface soil horizons, especially the forest floor (0-4 cm), had a serious impact on the N and P nutrient pools. Potassium was affected to a lesser degree. Landing rehabilitation measures may need to address this decline in soil fertility if full recovery of productivity is the objective.

There was little evidence on these sites that landing construction adversely affected stocking levels or foliar nutrient concentrations of regenerated lodgepole pine. Although seedlings were able to establish and grow in soil of densities greater than 1500 kg/m³, seedling height growth was severely affected. The difference in height between landing and off-landing lodgepole pine appeared to increase with time, as inferred from the study of landings of different ages. Although root systems were not examined, it seems likely that the decrease in seedling height is due to a combined effect of restricted root development and localized nutrient depletion around the seedling root. Within the current rotation it is doubtful whether the landings in the study area will produce commercial-sized timber comparable to the off-landing areas within the current rotation, without the institution of remedial measures. Until such time, landing areas should be considered under-productive and be excluded (or compensated for) in allowable cut calculations.

8 LITERATURE CITED

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APPENDIX 1. Statistical analysis of soil bulk density data by layer — Fort St. James

Analysis: ANOVA: single factor, split plot 0-30 cm

Source	df	SS	MS	F
Season	1	43 200	43 200	1.01
Error (a)	4	171 317	42 829	
Split-plot				
Treatment	1	81 120	81 120	20.67
Season x treatment	1	33 075	33 075	8.40
Error (b)	4	15 700	3 925	
Total	11	344 412		

0- to 10-cm layer

Source	df	SS	MS	F
Season	1	55 352	55 352	0.89
Error (a)	4	248 384	62 096	
Split-plot				
Treatment	1	1 283 802	1 283 802	75.26
Season x treatment	1	33 602	33 602	1.97
Error (b)	4	68 233	17 058	
Total	11	1 689 373		

10- to 20-cm layer

Source	df	SS	MS	F
Season	1	39 102	39 102	1.19
Error (a)	4	131 633	32 908	
Split-plot				
Treatment	1	722 752	722 752	276.28
Season x treatment	1	25 669	25 669	9.81
Error (b)	4	10 467	2 616	
Total	11	929 623		

20- to 30-cm layer

Source	df	SS	MS	F
Season	1	29 009	29 009	0.84
Error (a)	4	138 883	34 720	
Split-plot				
Treatment	1	541 875	541 875	336.83
Season x treatment	1	28 033	28 033	17.48
Error (b)	4	6 417	1 604	
Total	11	744 217		

APPENDIX 2. Statistical analysis of the percent increase in soil density — Fort St. James

Analysis: ANOVA: single factor (season of logging), three replications

0- to 10-cm layer

Source	df	SS	MS	F
Season	1	294	294	<1
Treatment	4	6188	1547	
Total	5	6482		

10- to 20-cm layer

Source	df	SS	MS	F
Season	1	434	431	4.67
Treatment	4	371	93	
Total	5	805		

20- to 30-cm layer

Source	df	SS	MS	F
Season	1	417	417	7.58
Treatment	4	218	55	
Total	5	635		

0- to 30-cm layer

Source	df	SS	MS	F
Season	1	771	771	4.67
Treatment	4	660	165	
Total	5	1431		

APPENDIX 3. Statistical analysis of soil N content (0-30 cm) — Fort St. James

Analysis: ANOVA: single factor, split plot

Source	df	SS	MS	F
Season	1	88 408	88 408	<1
Error (a)	4	859 447	214 861	
Split-plot				
Treatment	1	42 483	42 483	<1
Season x treatment	1	23 763	23 763	<1
Error (b)	4	293 678	73 420	
Total	11	1 307 780		

APPENDIX 4. Statistical analysis of soil N concentration (0-30 cm) — Fort St. James

Analysis: ANOVA: single factor, split plot

Source	df	SS	MS	F
Season	1	801	801	2.95
Error (a)	4	1085	271	
Split-plot				
Treatment	1	1728	1728	32.60
Season x treatment	1	5	5	<1
Error (b)	4	211	53	
Total	11	3830		

APPENDIX 5. Statistical analysis of soil P content (0-30 cm) —Fort St. James

Analysis: ANOVA: single factor, split plot

Source	df	SS	MS	F
Season	1	6 627	6 627	8.05
Error (a)	4	3 294	824	
Split-plot				
Treatment	1	26 134	26 134	36.91
Season x treatment	1	3 267	3 267	4.61
Error (b)	4	2 833	708	
Total	11	42 155		

APPENDIX 6. Statistical analysis of soil P concentration (0-30 cm) — Fort St. James

Analysis: ANOVA: single factor, split plot

Source	df	SS	MS	F
Season	1	602	602	31.68
Error (a)	4	75	19	
Split-plot				
Treatment	1	1302	1302	9.64
Season x treatment	1	352	352	2.61
Error (b)	4	539	135	
Total	11	2870		

APPENDIX 7. Statistical analysis of soil K content (0-30 cm) — Fort St. James

Analysis: ANOVA: single factor, split plot

Source	df	SS	MS	F
Season	1	7	7	<1
Error (a)	4	10 082	2 521	
Split-plot				
Treatment	1	1 180	1 180	0.78
Season x treatment	1	1 801	1 801	1.16
Error (b)	4	6 237	1 559	
Total	11	19 307		

APPENDIX 8. Statistical analysis of soil K concentration (0-30 cm) — Fort St. James

Analysis: ANOVA: single factor, split plot

Source	df	SS	MS	F
Season	1	61	61	<1
Error (a)	4	2411	603	
Split-plot				
Treatment	1	102	102	1.62
Season x treatment	1	200	200	3.17
Error (b)	4	251	63	
Total	11	3025		